Two Higgs Doublets from Fourth Generation Condensation

Gustavo Burdman

University of São Paulo

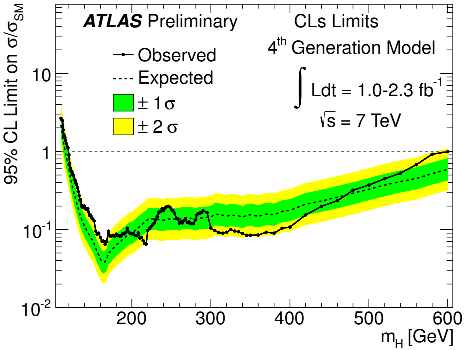
With *Carlos Haluch*, , arxiv:1109.xxxx

Outline

Is a Fourth Generation Still Viable ?

Higgs must either be:

- Light
  $m_h < 120$ GeV
- Heavy
  $m_h > 600$ GeV



Heavy quarks must be $m_{t'} > 450$ GeV, $m_{b'} > 400$ GeV

Possible Ways Out

- Dynamical explanation for $m_h > 600 \ \text{GeV}$
  - Fermion Condensation with low cutoff $\rightarrow$ Heavy Higgs/No Higgs
  - One Higgs doublet always $m_h > 700$ GeV
- More complicated scalar sector
  - Fermion condensation $\rightarrow$ Two-Higgs doublets at low energy
  - (Mostly) heavy scalar spectrum with different $\sigma \times BR$

Why a Fourth Generation ?

Heavy Chiral Fermions: strongly coupled to EWSB sector

- Top quark:

$$m_t \simeq v \qquad \Rightarrow \qquad y_t \sim 1$$

- If Heavy Fourth Generation $\Rightarrow y_4 > 1$

Higgs sector is strongly coupled

- Natural to assume composite Higgs sector

Why a Fourth Generation ?

Other motivation: (Holdom, Hou, Hurth, Mangano, Sultanasoy, Unel '09)

- New CP violation source for baryon asymmetry
- New sources of CPV in meson decays
- ...

Electroweak Symmetry Breaking

Composite EWSB Sector:

- Technicolor: Asymptotically free, unbroken gauge interaction

$$\Rightarrow \langle \bar{F}_L F_R \rangle \neq 0 \qquad \Rightarrow \mathrm{EWSB}$$

  F's are confined fermions, just as quarks in QCD.

- Alternative: gauge interaction spontaneously broken at $\Lambda \sim 1$ TeV
  $\Rightarrow$ F's un-confined heavy fermions with EW quantum #'s
  (E.g. Bardeen,Hill, Lindner '90, Hill '91)

EWSB from Fourth Generation Condensation

Ingredients:

- A Chiral Fourth Generation: $Q_4, U_{4R}, D_{4R}, L_4, E_{4R}, N_{4R}$
- New strong interaction at the $O(1)$ TeV scale:
  - E.g. Broken gauge symmetry $M \sim TeV$
  - Strongly coupled to 4th gen. $\Rightarrow \langle \bar{F}_4 F_4 \rangle \neq 0$

$$\Rightarrow m_4 \simeq (500 - 600) \text{ GeV}$$

- Other fermion masses: higher dimensional operators like

$$\frac{x_{ij}}{\Lambda^2} \bar{f}_L^i f_R^j \, \bar{U}_R U_L$$

Models of Fourth Generation Condensation

All ingredients present in AdS_5
(GB, Da Rold '07, GB, Da Rold, Matheus '09)

Extra dimensional theories in compact AdS_5 dual to strongly coupled theories in 4D:

- Naturally results in strongly coupled heavy fermions
- Higher-dimensional operators among light fermions suppressed by large UV scale Λ
- Build gauge theory in AdS_5 with one extra chiral generation and no Higgs .
- Minimal model: Only up-type 4G quark condenses

$$\Rightarrow \text{Only 1 Higgs doublet, } m_h \gtrsim 700 \text{ GeV}$$

Models of Fourth Generation Condensation

- More general *and* more natural: both up and down type quarks condense
- More natural: interaction must be nearly isospin invariant to avoid T parameter constraints
- More general: would need to fine tune interaction to avoid one condensation
- $\Rightarrow$ Two Higgs doublets at low energy

A Two Higgs Doublet from Fermion Condensation

(Luty '90, Luty, Hill, Paschos '90, GB, Haluch '11)

New fermions

$$Q^i = \left(\begin{array}{c} U^i \\ D^i \end{array} \right)_L, \quad U^i, D^i$$

with i gauge index of new interaction.

New Strong Interaction:

- Want un-confined fermions $\Rightarrow$ spontaneosly broken at scale M
- Massive bosons strongly coupled to Q^i, U^i and D^i
- E.g. If G^a color-octect $\Rightarrow$ $i = (1-3)$ is color index, Q^i, U^i and D^i can be fourth-generation quarks

Electroweak Symmetry Breaking

New strong interactions $\Rightarrow$ four-fermion operators

$$\mathcal{L}_{\rm 4f} = \frac{g_L g_u}{M_G^2}\bar{Q}U\bar{U}Q + \frac{g_L g_d}{M_G^2}\bar{Q}D\bar{D}Q$$

with g_L, g_u, g_d gauge couplings. If

$$\begin{aligned} g_L g_u &> \frac{8\pi^2}{N_c} \Rightarrow \langle \bar{Q}U \rangle \neq 0 \\ g_L g_d &> \frac{8\pi^2}{N_c} \Rightarrow \langle \bar{Q}D \rangle \neq 0 \end{aligned}$$

One doublet condensing $\Rightarrow SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$

EWSB and Low Energy Scalar Spectrum

Four-fermion interactions $\longleftrightarrow$ Yukawa interactions

$$
\begin{aligned}
\mathcal{L}_{\mathrm{eff.}} &= Y_U(\bar{Q}\tilde{\Phi}_U U + \mathrm{h.c.}) + Y_D(\bar{Q}\Phi_D D + \mathrm{h.c.}) \\
&\quad - M_G^2 \Phi_U^\dagger \Phi_U - M_G^2 \Phi_D^\dagger \Phi_D
\end{aligned}
$$

with

$$
Y_U^2 = g_L g_u, \qquad Y_D^2 = g_L g_d\ , \qquad \tilde{\Phi}_U = -i\sigma_2 \Phi_U^*
$$

with hypercharges $h_U = -1/2$, $h_d = 1/2$.

EWSB and Low Energy Scalar Spectrum

At $\mu < M_G$:

- Scalars develop kinetic terms

$$\mathcal{L}_{\text{kin.}} = Z_{\Phi_U}(\mu)(D_\mu \Phi_U)^\dagger D^\mu \Phi_U + Z_{\Phi_D}(\mu)(D_\mu \Phi_D)^\dagger D^\mu \Phi_D$$

  with the compositness BCs $Z_{\Phi_U}(M_G), Z_{\Phi_D}(M_G) = 0$.

- They get VEVs if four-fermion couplings super-critical:

$$\langle QU \rangle \neq 0 \leftrightarrow \langle \Phi_U \rangle \neq 0$$
$$\langle QD \rangle \neq 0 \leftrightarrow \langle \Phi_D \rangle \neq 0$$

- Effective Two-Higgs doublet spectrum at low energy

Low Energy Scalar Spectrum

At $\mu < M_G$ all couplings get renormalized and some generated. E.g. :

$$Y_U \to \frac{Y_U}{\sqrt{Z_{\Phi_U}}}, \qquad Y_D \to \frac{Y_D}{\sqrt{Z_{\Phi_D}}}$$

$$\begin{aligned} \mu_U^2 &= M_G^2 - \frac{g_L g_u N_g}{8\pi^2}\left(M_G^2 - \mu^2\right) \\ \mu_D^2 &= M_G^2 - \frac{g_L g_d N_g}{8\pi^2}\left(M_G^2 - \mu^2\right) \end{aligned}$$

We ca see that $m_U^2 < 0$ and $m_D^2 < 0$ for super-critical couplings

$\Rightarrow$ $V(\Phi_U, \Phi_D)$ with $\langle \Phi_U \rangle = v_U$, $\langle \Phi_D \rangle = v_D$

$\Phi_U - \Phi_D$ Mixing and Peccei-Quinn Symmetry

Theory is invariant under

$$Q \to e^{-i\theta} Q \qquad U \to e^{i\theta} U \qquad D \to e^{i\theta} D$$

$$\Phi_U \to e^{2i\theta} \Phi_U \qquad \Phi_D \to e^{-2i\theta} \Phi_D \ ,$$

forbids mixing term $\mu_{UD}^2 (\Phi_U^\dagger \Phi_D + h.c.)$ in $V(\Phi_U, \Phi_D)$.

This results in $M_A = 0$

Instantons Induce M_A

Fermionic equivalent of mixing term

$$\mathcal{L}_{\rm mix} = G_{UD}(\bar{Q}D\bar{U}^c\tilde{Q} + \text{h.c.})\ , \qquad (\tilde{Q} = -i\sigma_2 Q)$$

But this is generated by 't Hooft fermion determinant (Hill '95)

$$\mathcal{L}_{inst.} = \frac{k}{M_G^2}\,\mathbf{det}\left[\bar{Q}_L Q_R\right]$$

with $k \sim O(1)$.

$\Rightarrow$ Instantons of new strong interactions responsible for M_A

Scalar Spectrum

Scalar potential generated by fermion loops

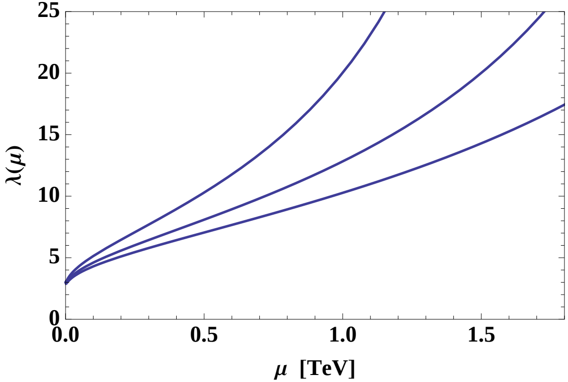
$$\begin{aligned} V(\Phi_U, \Phi_D) &= \mu_U^2 |\Phi_U|^2 + \mu_D^2 |\Phi_D|^2 + \mu_{UD}^2 ({\Phi_U}^\dagger \Phi_D + \mathrm{h.c.}) \\ &+ \frac{\lambda_1}{2} |\Phi_U|^4 + \frac{\lambda_2}{2} |\Phi_D|^4 + \lambda_3 |\Phi_U|^2 |\Phi_D|^2 + \lambda_4 |{\Phi_U}^\dagger \Phi_D|^2 \end{aligned}$$

Couplings Y_U, Y_D, λ_i, μ_U, μ_D, μ_{UD} run down by using RGEs

$\Rightarrow$ scalar spectrum

Running to Low Energies

Solutions for $\lambda_1(\mu)$ for $M_G = 2, 3, 4$ TeV



Scalar Spectrum

$$\begin{aligned}
A &= \sqrt{2}\left(Im[\Phi_D^0]\cos\beta - Im[\Phi_U^0]\sin\beta\right) \\
h &= \sqrt{2}\left(-Re[\Phi_U^0]\sin\gamma + Re[\Phi_D^0]\cos\gamma\right] \\
H &= \sqrt{2}\left(Re[\Phi_U^0]\cos\gamma + Re[\Phi_D^0]\sin\gamma\right] \\
H^\pm &= \Phi_D^\pm\cos\beta - \Phi_U^\pm\sin\beta
\end{aligned}$$

$\tan\beta = v_U/v_D \simeq 1$. The CP-even mixing is

$$\tan 2\gamma = \frac{\mu_{UD}^2 + (\lambda_3 + \lambda_4)v^2\sin 2\beta/2}{\mu_{UD}^2 + \lambda_4 v^2\cos 2\beta/2}$$

Scalar Masses

E.g.: Pseudo-scalar mass

$$\mu_{UD}^2 = \frac{k\, v^2}{2 M_G^2} \frac{\lambda_1 \lambda_2 \cos^2\beta \sin^2\beta}{\left[1 - kv^2(\lambda_1 \cos^2\beta \cot\beta + \lambda_2 \sin^2\beta \tan\beta)/(2M_G^2)\right]}$$

and the pseudo-scalar mass is

$$M_A^2 = -2 \frac{\mu_{UD}^2}{\sin 2\beta}$$

Scalar Masses

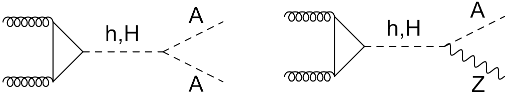
For $k = (0.1 - 1)$

	$M_G = 2$ TeV	$M_G = 3$ TeV	$M_G = 4$ TeV
M_A	(26-118) GeV	(15-59) GeV	(10-39) GeV
M_h	(548-580) GeV	(459-467) GeV	(422-425) GeV
M_H	(651-732) GeV	(530-537) GeV	(482-585) GeV
$M_{H^\pm}$	(603-719) GeV	(495-512) GeV	(453-459) GeV

- Heavy $(h, H, H^\pm) \simeq (400 - 700)$ GeV depending on (k, M_G)
- Light $A \simeq (10 - 120)$ GeV

Phenomenology

- Usual h, H decay channels suppressed in favor of AA, A, Z

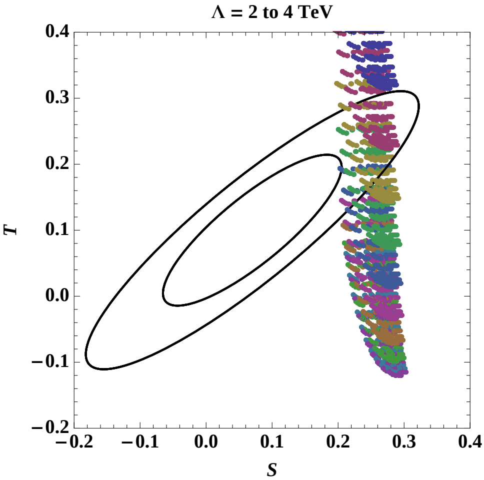


- If condensing fermions carry color (4G quarks) $\rightarrow$ $\sigma_{\rm prod.}(gg \rightarrow (h, H, A)) \simeq (6-7)$ SM values
- If new fermion colorless, no enhancement of $\sigma_{\rm prod.}$. But scalar spectrum still same.

Electroweak Precision Constraints

Constraints in the S-T plot (68% and 95% C.L. contours

Parameter space of scalar sector (k, M_G) + fourth generation



Flavor

- Dynamics at the high scale introduce higher dimensional operators such as
$$\frac{x_{ij}}{\Lambda^2}\ \bar{f}_L^i f_R^j\ \bar{U}_R U_L$$
- Can always accommodate Φ_U only couples to up-type quarks, Φ_D only to down-type quarks and charged leptons
- PQ symmetry softly broken $\Rightarrow$ mixing does not induce FCNCs at tree level
- Loop effects: $H^\pm$ too heavy to give important effects in $b \to s\gamma$, etc.

Summary/Outlook

- 4th Generation still not excluded by Higgs searches
- Composite 2HDM with light A and heavy $(h, H, H^{\pm})$ is a natural consequence of fermion condensation
- If new fermions carry color:
  - We will see them soon ($m_{t'} > 450$ GeV)
  - $\sigma(h, H, A)$ larger than in standard 2HDM
  - But preferred decay channels are $(h, H) \to (A, A), (A, Z)$
- If new fermions colorless, unusual scalar spectrum still hint of fermion condensation